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Conceptual Design of a 260 mm Bore 5 T Superconducting Curved Dipole Magnet for a Carbon Beam Therapy Gantry

S. Caspi, D. Arbelaez, H. Felice, R. Hafalia, D. Robin, C.Sun, W. Wan and M. Yoon

Abstract—**A conceptual design of curved superconducting magnet for a carbon therapy gantry has been proposed. The design can reduce the gantry's size and weight and make it more comparable with gantries used for proton therapy. In this paper we report on a combined function, 5 T, superconducting dipole magnet with a 260 mm bore diameter that is curved 90 degrees at a radius of 1269 mm. The magnet superimposes two layers of oppositely wound and skewed solenoids like windings, energized in a way that nulls the solenoid field and doubles the dipole field component. Furthermore, the combined architecture of the windings can create a selection of field terms that are off the near-pure dipole field. Combined harmonics such as a quadrupole and sextupole are needed to adjust the beam trajectory. Ways to adjust the field and beam trajectory, magnet size and assembly, structure and pre-stress are considered.**

***Index Terms*—Carbon Therapy, gantry, superconducting magnet, curved dipole.**

I. INTRODUCTION

ION beam cancer therapy is the use of ion beams to kill cancer tumors. By far the most common ion uses in ion beam therapy are protons (~90%) followed by carbon beams (~10%). As compared with protons, carbon ions have certain physical and biological properties that are advantageous as compared with protons. However the energies required for carbon beams are significantly higher than for proton beams. For example, to penetrate 30 cm depth a proton beam requires 250 MeV versus a carbon beam that requires 430 MeV/u. In addition to the larger accelerators needed to accelerate the beams, the beam-lines require larger/stronger magnets to bend the carbon beam and direct it towards the patient. This tends to make carbon facilities larger and more expensive and is particularly true for gantries. Gantries (see Fig. 1) are rotatable beam-lines that allow the beam to be directed at the patient at any arbitrary angle without having to tilt the patient [1]. At the present time there exists only one carbon therapy gantry at the Heidelberg Ion Therapy Center (HIT) [2, 3]. It is 50% larger and 5 times heavier than similar proton gantries.

In this study we assume a fixed "iso-centric" gantry with parallel scanning that is a variation of a Pavlovic design, Fig. 1. The focal point of the beam remains fixed as the gantry rotates and the beam uses point to parallel scanning within the final 90 degrees sweep of the dipole [4]. In the case of HIT, the 90 degrees magnet weighs 90 tons that is 65% of the weight of the entire rotating transfer system. High-field superconducting magnet can be used to reduce the over-all size and weight of carbon gantries to closely match those used in protons. In this paper we describe the main features of a 5 T combined function curved superconducting dipole magnet and address issues of field quality size and weight.

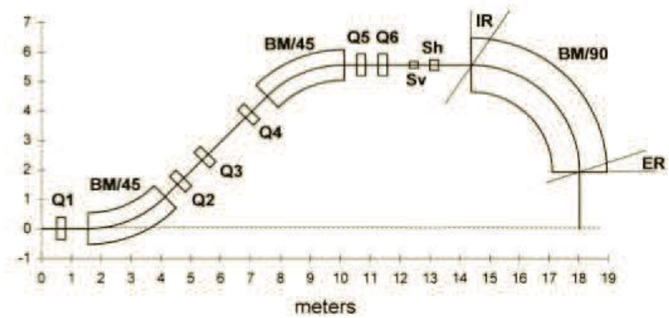

Fig. 1. Magnetic layout of an isocentric gantry with bending magnets (BM), quadrupole magnet (Q), horizontal and vertical scanning magnets (Sv and Sh).

II. A COMBINED FUNCTION TILTED MAGNET

A. Large Aperture Final Bend

To estimate the magnet bore size and nominal field region we need to consider the size of the tumor. To target the tumor without moving the gantry, a large bore and specific field during transverse scanning is required to assure point to parallel beam optics. The nominal field region for the HIT gantry is 20 cm × 20 cm and the large bending angle suggests a field that is not necessarily a pure dipole. Large nonlinear terms in the magnetic field would be needed to focus and bend the beam. Introducing gradient field terms to the design of the magnet, the beam can remain parallel at the patient.

B. Basic Concept

Superimposing two solenoid-like windings that are oppositely skewed (tilted) with respect to a cylindrical axis, the combined current density on the surface is cosine-theta

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like and the resulting magnetic field in the bore is a pure dipole [5-10]. Good field quality along the axis is achieved without optimization (no wedges) and end-harmonics naturally integrate to zero. We have extended this concept to curved magnets by forming the windings in a torus.

C. Extension to a Torus

Winding a dipole in a torus requires placement of the windings on a convex surface (the torus OD) and, as the conductor comes around, along a concave surface along the torus ID (Fig. 2). Placing the conductor under tension on the inner radius of a torus poses a technical challenge in the way windings are held in position – the winding tendency is to slide off the torus (Fig.2 left). The present concept maintains winding tension on both the inner and outer surface of the torus by controlling the tilt winding angle (Fig.2 right). This way the magnet remains compact and better constrained to handle Lorentz forces.

Fig. 2. Top view of windings on a torus. Concave windings (left) and convex windings (right). Winding tension is more easily maintained along a convex path.

D. Winding Parameterization and Optimization

We demonstrate how placing windings on a torus leads to a predetermined combined-function multipole field that satisfies constraints of the final bend. To arrive at a winding solution we describe two methods - one by using a Genetic Algorithms (GA) [11], and a second by using an approximate analytic method that requires iteration. The torus forms a surface of constant R on to which only φ and θ, φ=f(θ), are needed to describe a winding path (Fig. 3). Using the GA method to search for winding solutions we parameterized the path on the surface of torus using the relation:

$$\varphi = \theta/n + a_1 \sin\theta + a_2 \sin 2\theta + a_3 \sin 3\theta + \cdots \quad (1)$$

n is the number of turns on a complete torus, and a_1, a_2, a_3,.. are coefficients that determine the multipole field components. The magnetic field inside the torus is numerically evaluated from the windings using the Biot-Savart law and further use to study beam dynamics (with the Differential Algebra code COSY INFINITY [12]) to define the trajectory [13].

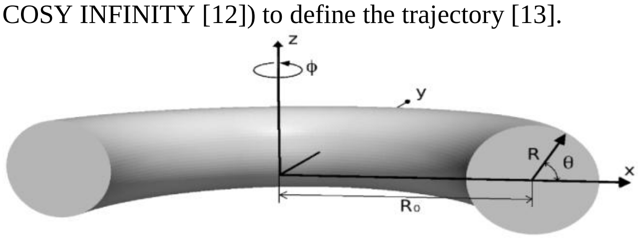

Fig. 3. Toroidal coordinates

The second approach assumes a torus surface (membrane) with a current density that satisfies the divergence free relation between its components. This approach assumes current density components that asymptotically approach known behavior when the torus radius is large approaching that of a straight cylinder. Assuming a relation between Cartesian and a toroidal coordinates (Fig. 3),

$$\begin{aligned} x &= (R_0 + R\cos\theta)\cos\varphi \\ y &= (R_0 + R\cos\theta)\sin\varphi \\ z &= R\sin\theta \end{aligned} \quad (2)$$

where R_0 is radius of the torus and R is the radius of the bore, the divergence-free relation, $\nabla \cdot J(\theta,\varphi) = 0$,can be written as:

$$\frac{1}{R}\frac{\partial J_\theta}{\partial \theta} - \frac{J_\theta \sin\theta}{(R_0 + R\cos\theta)} + \frac{1}{(R_0 + R\cos\theta)}\frac{\partial J_\varphi}{\partial \varphi} = 0 \quad (3)$$

where J_θ and J_φ are the transverse and axial current density on the torus surface. Expressing the current density on the torus as the series:

$$J_\varphi(\theta) = \sum_{n=1}^{M} J_{0n}\cos n\theta \quad (4)$$

(n is the harmonic number and J_{0n} a constant), substituting (4) into (3) and performing an integration the resulting transverse current density J_θ is equal to a constant J_{00} (equal to its value at θ=π/2). To determine the relation for a current line, *I*, (the wire path) we integrated (3)

$$I = J_\theta(R_0 + R\cos\theta)\,d\varphi = J_{0\theta}R_0 d\varphi = J_\varphi R d\theta \quad (5)$$

and arrive at φ=f(θ),:

$$\varphi = \frac{R}{R_0}\sum_{n=1}^{M}\frac{J_{0n}}{n \cdot J_{0\theta}}\sin n\theta \quad (6)$$

If we wish to replace the current density with the field, we use the relations (by approximation for a straight coil):

$$J_{0n} = \frac{2B_{0n}}{\mu_0}, \qquad J_{0\theta} = \frac{B_{0-sol}}{\mu_0},$$

(μ_0 is the permeability) and rewrite (6) as:

$$\varphi = \frac{R}{R_0}\frac{2}{B_{0-sol}}\left(B_d \cdot \sin\theta + \frac{G \cdot R}{2}\sin 2\theta + \frac{S \cdot R^2}{3}\sin 3\theta + \cdots\right) \quad (7)$$

where B_d, G, and S are the dipole, quadrupole and sextupole terms respectively.

The wire path can now be used to calculate the field directly from Biot-Savart law, and field harmonics on the mid-plane compared with expected harmonics use in (7). The limiting asymptotic field approximation diverts the purity of each harmonic term by adding non-linear terms (usually small) that could subsequently be significantly reduced by iteration. For example a path calculated for a pure dipole term will generate higher harmonics that will be included and recalculated (with an inverted sign) on the second pass, generating a revised winding set with the desired purity. As an example this method was used to generate three pure fields; a dipole, quadrupole and sextupole within a torus (Fig. 4).

III. A Combined Function Gantry Magnet

A. A 90 degrees Curved Dipole

We have used the above technique to generate the windings of a 90 degrees bend dipole with a 260 mm bore and a 5 T field. The dimensions of the coil and structure are listed in

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Table I with computational results in Table II. After conceptualizing the outer structure the resulting 14 ton magnet is dominated by the weight of the iron. The two superimposed layers null the solenoid field and simultaneously double the main dipole field. A tilt angle was chosen to maintain tension during winding. A 2 dimensional program, POISSON (with axisymmetry), was first used to estimate the size of the iron and calculate the magnet stored energy (Fig. 5). The 3 dimensional program Opera3D was then used to address coil "ends" contribution and study the beam trajectory. Several attempts were made to adjust the iron including placing the iron eccentric to the coil. To attain the point-to-parallel trajectory optimization, a dipole field B_d of 5.0 T in the bore center with a -2.26 T/m quadrupole (G) and a 1.30 T/m^2 sextupole (S) were required (Figs. 6 and 7).

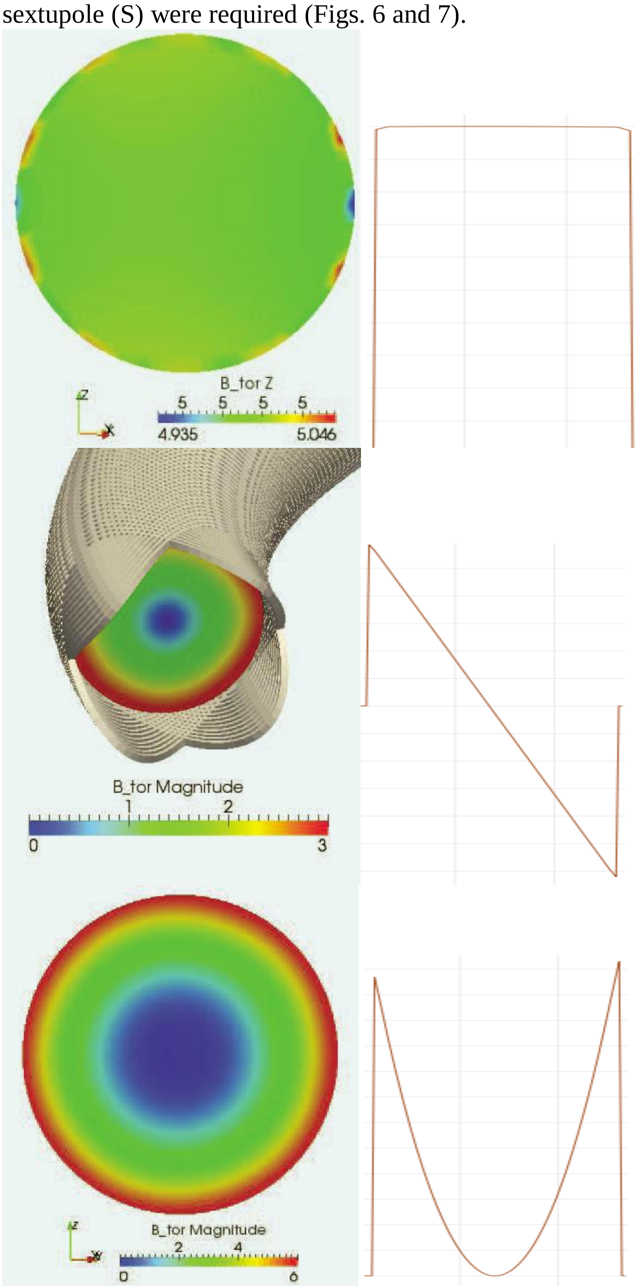

Fig. 4. A pure dipole (top), quadrupole (center) and sextupole (bottom) in a toroid. Colors represent field magnitude (left) and a mid-plane field (right).

B. Magnet Assembly and Applied Pre-stress

The technology developed for Nb_3Sn magnets is used to design and fabricate the magnet. The application of the pre-stress to the coils (Fig. 8) utilizes "key and bladder technology" [14] to simultaneously compress the inner coil and stretch the outer aluminum shell. The final assembly is made of two subassemblies, a structural subassembly that includes the outer iron yoke and aluminum shell, and a coil-pack subassembly that includes two load pads (G10) locked around the coil. When the two subassemblies are assembled together, bladders are placed in between the load pads and the yokes, pressurized, opening interference-key gaps into which shimmed keys are inserted. When the bladders are deflated and removed the stretched outer shell contracts and compress the yokes against the load pads and coil through the interference keys – locking the subassemblies together. The coils are now in compression and the outer shell in tension. Initial Stress analysis was done in 2D using ANSYS (Fig. 9).

TABLE I MAGNET GEOMETRY

Torus curvature radius	1269 mm
Clear bore diameter	250 mm
Coil inner diameter	260 mm
Coil outer diameter	304 mm
Iron inner diameter	400 mm
Iron outer diameter	1080 mm
Aluminum shell outer diameter	1115 mm
Magnet weight	14 metric-ton
Weight of structure (mostly iron)	90 %

TABLE II MAGNETIC PARAMETERS

Central dipole field	5 T
Quadrupole term	-2.26 T/m
Sextupole term	1.3 T/m^2
Number of layers	2
Turns per slot	3
Current per turn	6.9 kA
Engineering current density	415 A/mm^2
Operating point	80 %
Total stored energy	1.55 MJ
Cold coil azimuthal stress at 5T	-104 MPa
Outer Al shell cold stress at 5T	150 MPa

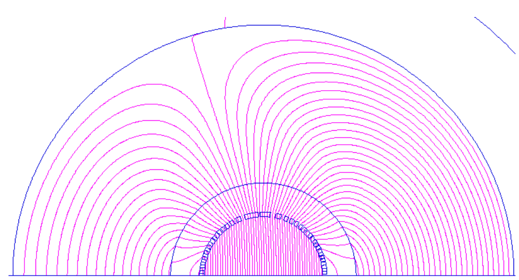

Fig. 5. 2D flux plot across the torus.

C. Future Plans

To reach various depths within a tumor the beam energy has to change and so will the magnetic field. Ramps of the order of 0.065 T/s are required to do so and heat generated during the ramp will have to be removed using a cryogenic system. Work on estimating the heat loss and the cryogenic cooling system requirements have just started.

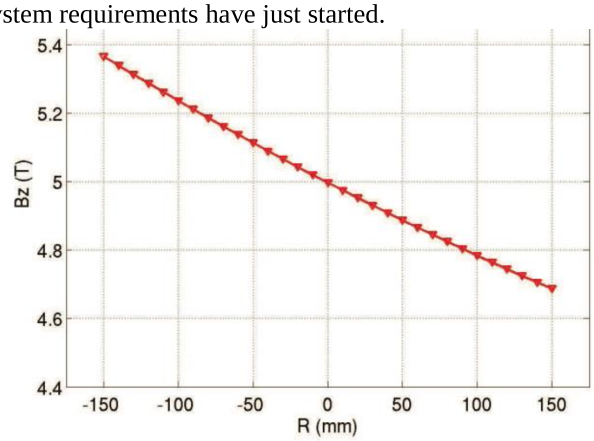

Fig. 6. The vertical field (Bz) and gradient across the mid plane of the torus. The center dipole is 5 T with gradients of -2.26 T/m and 1.3 T/m^2

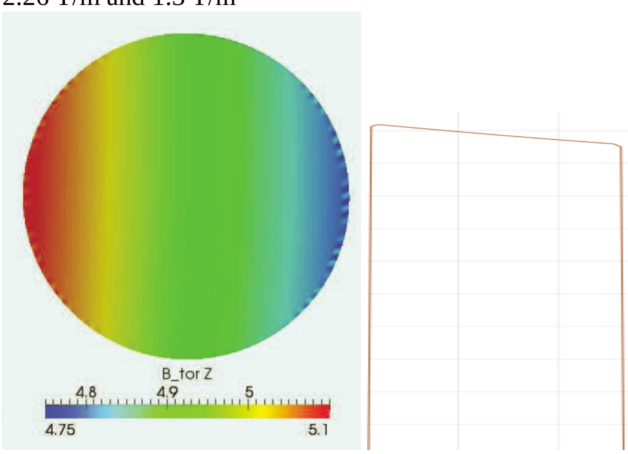

Fig. 7. The combined function dipole field used in the present design (superposed with a quadrupole and sextupole terms).

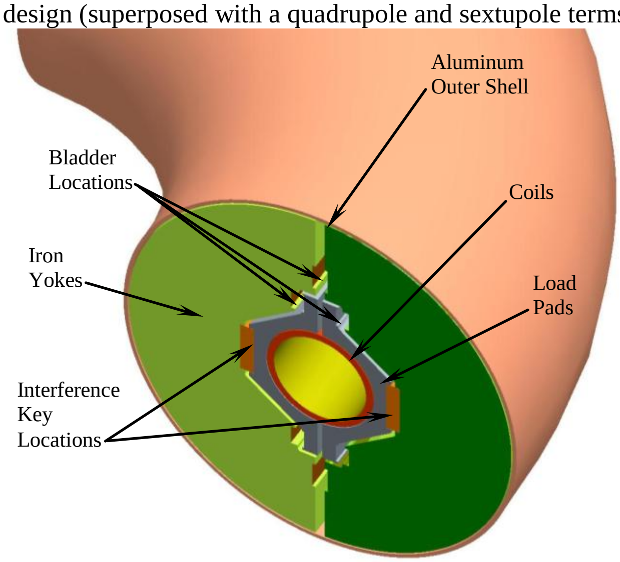

Fig. 8. A CAD view of the 90 degrees bend dipole.

IV. Conclusion

Concepts for winding a combined function superconducting coil in a torus and the design of a curved dipole magnet are proposed for a carbon therapy gantry system. The coil optimization for controlling beam tracking results in nearly linear position response while minimizing distortion within the scanning range. The coil optimizations and magnet structure is a first step in understanding the feasibility of a complete system. Future plans include ramping rate studies and cooling.

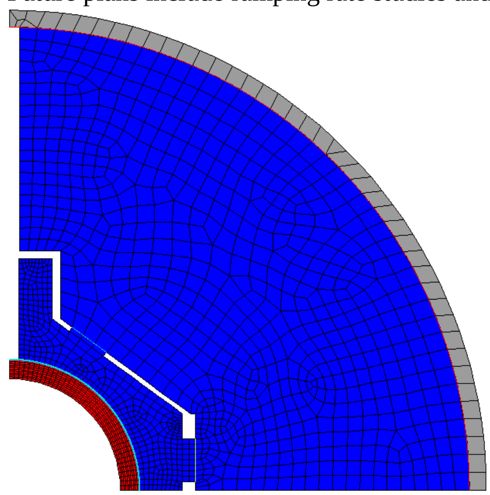

Fig. 9. An ANSYS model used for stress analysis.

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